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(54) Abstract Title
**Optical Amplifiers**

(57) An optical amplifier comprises a silicon-based substrate (1) having a gain region (7) for amplifying an optical signal and a rare earth based organic light-emitting device (13) for producing excited rare earth ions in the gain region. The optical signal may be amplified by stimulated emission from the excited rare earth ions. When the rare earth is erbium the optical amplifier can provide amplification at 1.5 μm. Where the rare-earth ion is neodymium it can provide amplification at 1.3 μm.

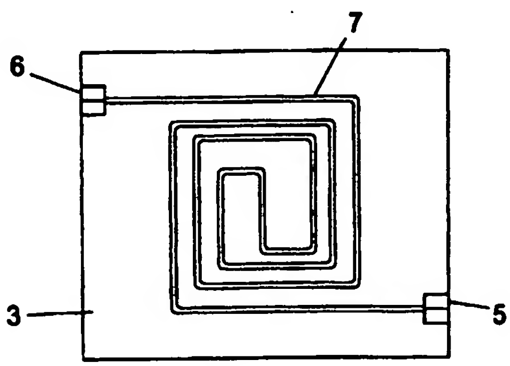


Fig. 2A

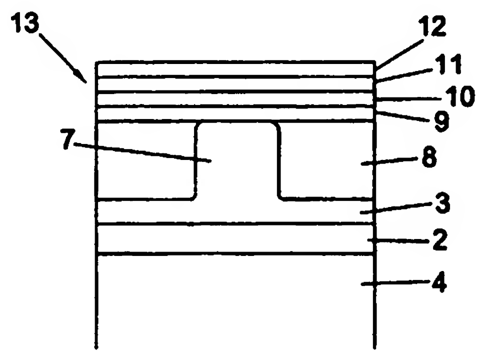


Fig. 4

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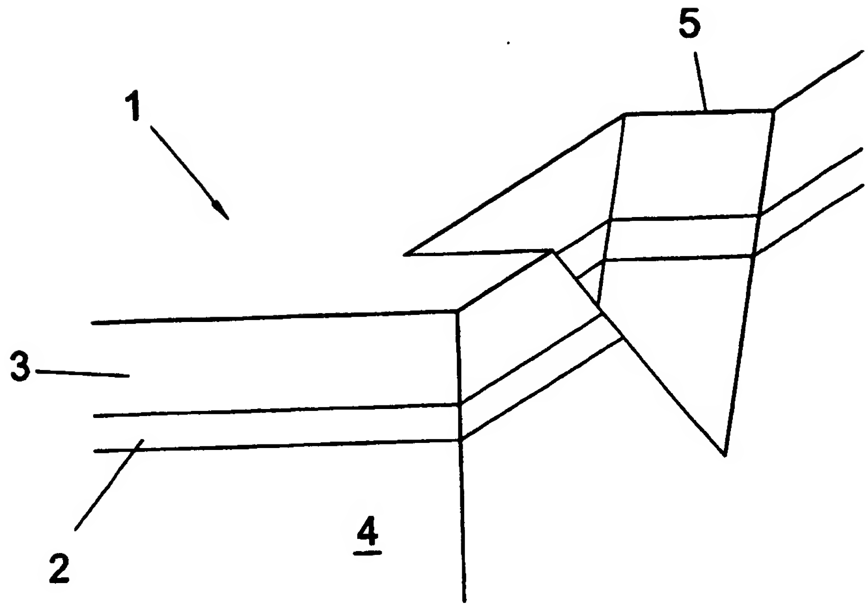


Fig. 1A

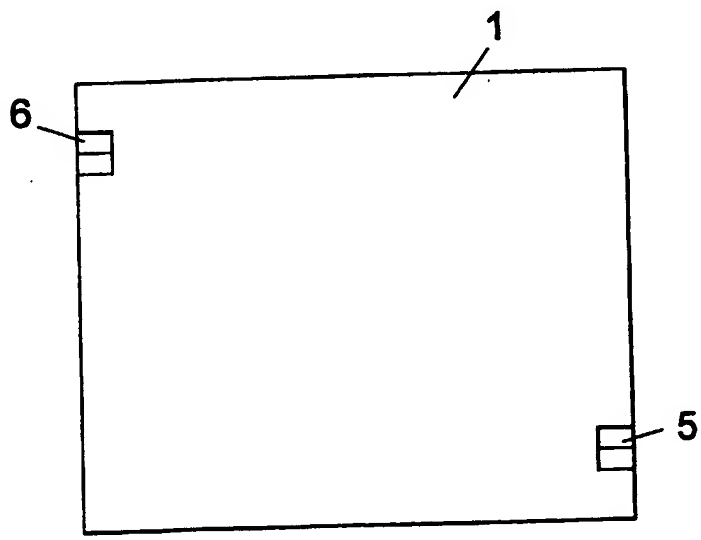


Fig. 1B

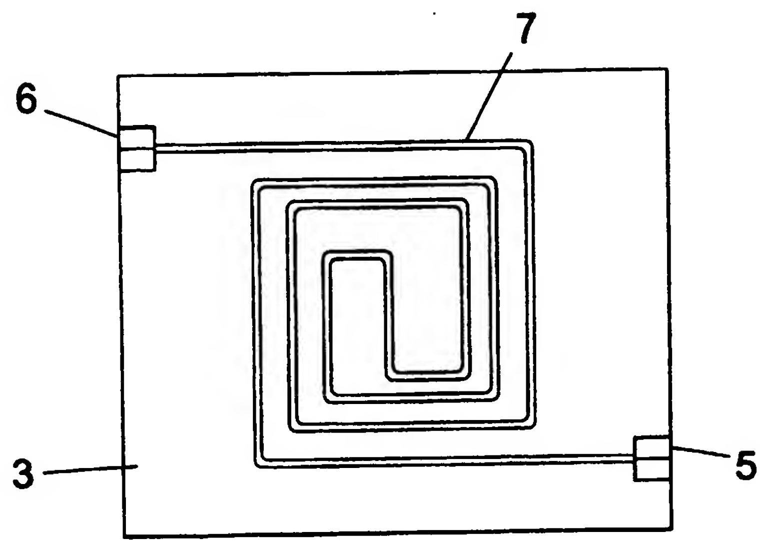


Fig. 2A

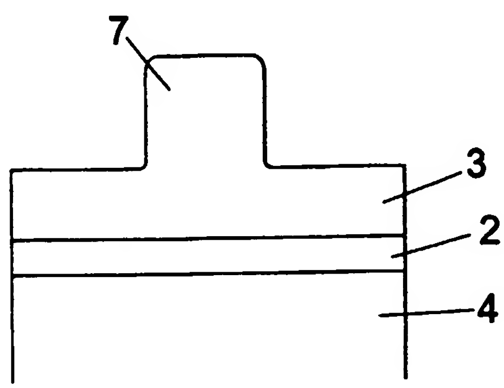


Fig. 2B

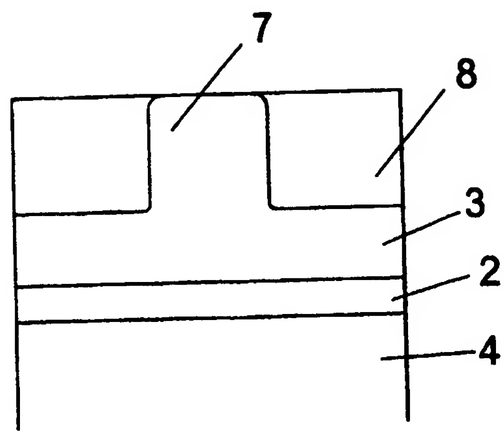


Fig. 3

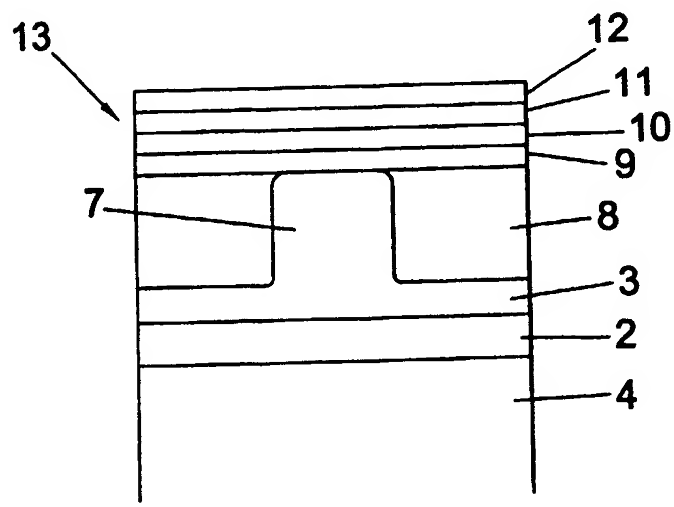


Fig. 4

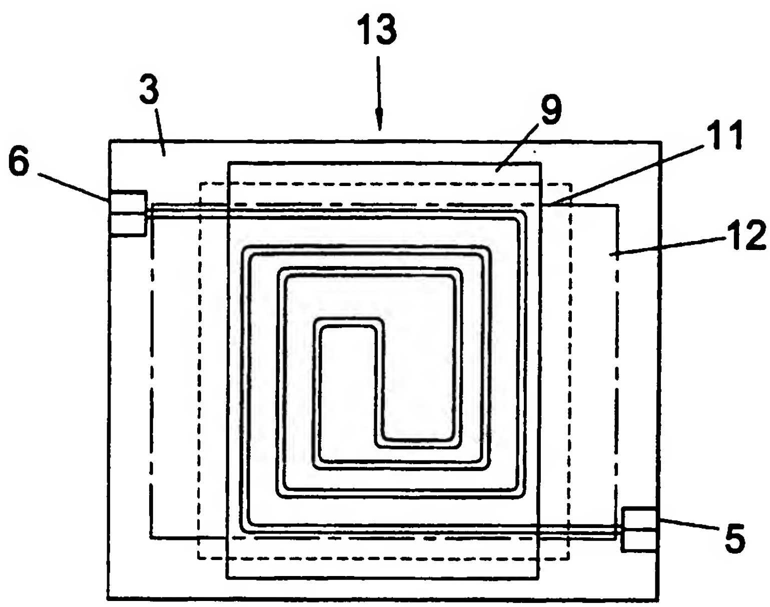


Fig. 5

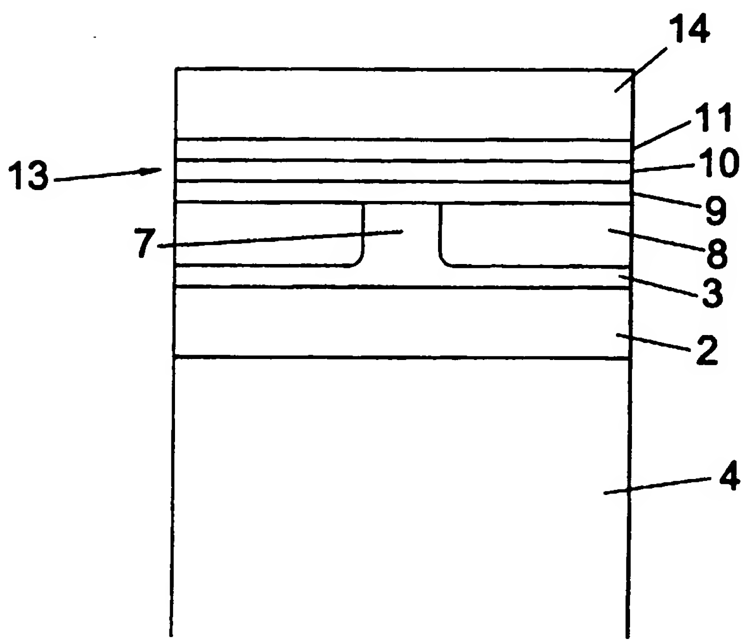


Fig. 6

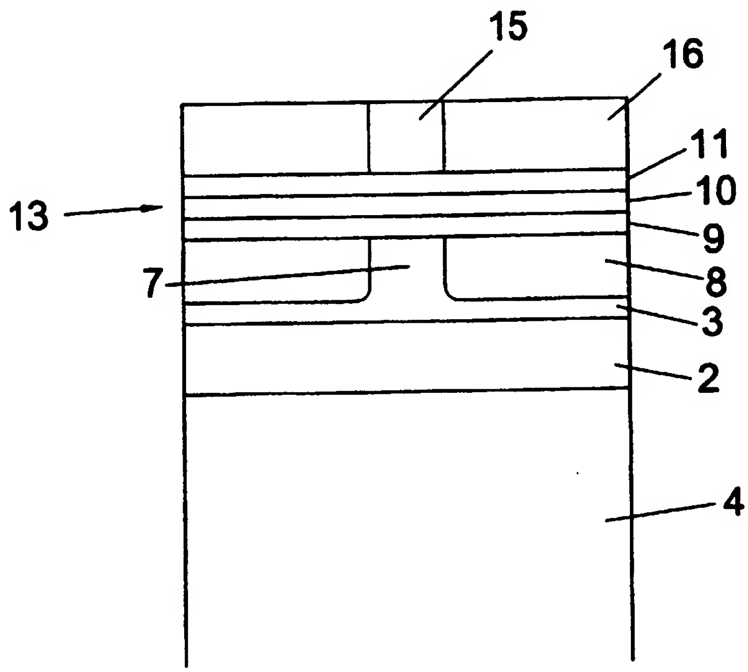


Fig. 7

## OPTICAL AMPLIFIERS

The present invention relates to optical amplifiers.

As used herein, the words "light emitting device" and "light-emitting diode" are used to describe a device which emits electromagnetic radiation of any wavelength, and are not intended to be limited to systems emitting light in the visible spectrum. The word "optical" is intended to apply to electromagnetic radiation of any wavelength and is not intended to be limited to light in the visible spectrum.

Current long distance optical fibre telecommunication systems operate at wavelengths of 1.5 μm or 1.3 μm, since these are the low-loss and low-dispersion windows for silica optical fibres. However, despite these wavelengths having very low losses in these fibres, the optical signals still need to be regularly regenerated by optical amplifiers spaced at intervals along the fibre. For wavelengths around 1.5 μm, the current technology for achieving this is the Erbium Doped Fibre Amplifier (EDFA) which consists of a length of optical fibre doped with erbium ions. Erbium is particularly useful as it has an intra-atomic transition within the 4f level of the $Er^{3+}$ ion between the first excited state ($^4I_{13/2}$) and the ground state ($^4I_{15/2}$) which emits at ~1.54 μm. The erbium ions are excited using external lasers so that, when the optical signal to be regenerated passes through the fibre, it causes stimulated emission from the excited erbium ions. This has the effect of amplifying the optical signal.

This system works efficiently but necessitates the provision of external pumping lasers, which require a significant input of energy and which contribute towards the bulk of the device.

In accordance with a first aspect of the present invention there is provided an optical amplifier comprising a silicon-based substrate having a gain region for amplifying an optical signal, an organic light-emitting device containing a rare earth being provided for producing excited rare earth ions in the gain region.

This enables the provision of excited rare earth ions directly in the gain region without the need for external lasers. The signal can then be amplified by stimulated emission from the rare earth ions in the normal way.

The gain region is conveniently formed by a waveguide on the substrate, thus permitting the size of the device to be kept to a minimum.

The waveguide preferably follows a coiled path on the substrate. This makes maximum use of the surface area of the substrate and allows a long gain region to be formed on a small substrate.

The waveguide is preferably a ridge or buried-ridge waveguide and may be formed from layers of dielectric material deposited on the substrate.

The amplifier preferably comprises coupling means for coupling optical fibres to the amplifier. These coupling means may be V-shaped grooves in the substrate. Silicon is easily micromachined to produce such grooves and this enables simple and accurate positioning of the fibres so as to produce a simple, low-cost amplifier.

The rare earth used in the light-emitting device may be erbium, enabling stimulated emission (and therefore amplification) of light at 0.98 and 1.53μm. If amplification is required at other wavelengths other rare earths can be used. Emission centred on 0.98, 1.064 and 1.33 μm has been demonstrated using neodymium, and emission centred on 0.98 μm using ytterbium.

The preferred embodiments of the invention provide a solid state optical amplifier based on silicon technology that can provide optical amplification at a number of wavelengths including 1.3 μm and 1.5 μm. The device has the advantage that it can be reasonably small, easily fabricated onto a planar substrate and can operate using a single DC power supply.

Some preferred embodiments of the invention will now be described by way of example only and with reference to the accompanying drawings in which:

Figure 1A shows a schematic diagram of a silicon-on-insulator substrate into which has been etched a pair of V-grooves for locating an optical fibre to the end of the waveguide structure, Figure 1B being a plan view of the substrate;

Figure 2A is a plan view of the substrate of Figure 1 following the etching of a waveguide structure, Figure 2B being a cross-sectional view of the substrate and waveguide structure;

Figure 3 is a cross sectional view of the assembly of Figure 2 following planarisation.

Figure 4 shows a cross section through the waveguide structure of Figure 3 following deposition of an indium tin oxide (ITO) anode layer, organic layers and top metallisation;

Figure 5 shows a plan view of the waveguide structure of Figure 4;

Figure 6 shows a cross section through a second embodiment of a device in accordance with the invention; and

Figure 7 shows a cross section through the device of figure 6 following etching of the top contact and planarisation.

Electroluminescence from organic materials has been the subject of increasing interest in recent years. In 1987 Tang and VanSlyke [C.W. Tang and S.A. VanSlyke, Appl. Phys. Lett., 51(12), 913, 1987] demonstrated that it was possible to obtain visible electroluminescence, with a peak emission wavelength of ~510 nm, from aluminium tris-(8-hydroxyquinoline) (AlQ) based diodes. Considerable work has been done since then on improving the brightness, efficiency and reliability of organic light emitting devices (OLEDs), and AlQ has remained one of the most widely used emitting materials.

It has recently been demonstrated by R.J.Curry and W.P. Gillin, Appl. Phys. Lett., 75(10), 1380, 1999 and O.M. Khreis, R.J. Curry, M. Somerton, W.P. Gillin, J. Appl. Phys., 88(2), 777, 2000 that it is possible to incorporate rare earth ions into organic molecules which can be incorporated into an organic light emitting diode (OLED) to produce infrared emission. Emission has been demonstrated centred at 0.98 and 1.53 μm using erbium, 0.9, 1.064 and 1.33 μm using neodymium and 0.98 μm using ytterbium. Furthermore, it has been demonstrated by R.J. Curry, W.P. Gillin, A.P. Knights, R. Gwilliam, Appl. Phys. Lett., 77(15), 2271, 2000 that it is possible to integrate an erbium containing device directly onto a silicon substrate to obtain 1.53 μm emission from the silicon.

The fabrication of an optical amplifier making use of such emission is described with reference to Figures 1 to 5.

Figure 1 shows a silicon-on-insulator substrate 1 comprising a silicon oxide layer 2 sandwiched between two silicon layers 3, 4. V-shaped grooves 5, 6 (see Figure 1B) have been etched into the substrate 1. The grooves 5, 6 are sized and arranged so as to locate optical fibres (not shown) accurately to the ends of a waveguide that will be subsequently etched. The V-shaped grooves 5, 6 are fabricated using standard silicon photolithography and anisotropic chemical etching.

As shown in Figure 2, following the fabrication of the V-shaped grooves 5, 6, a waveguide structure 7 is defined by photolithography. Standard chemical etching is then used to etch away part of the overlying silicon 3 to produce a ridge waveguide structure 7. The dimensions of the waveguide 7 will be dependent on the wavelength of the light with which it is designed to operate. The coiled nature of the waveguide 7 allows for a longer waveguide to be fabricated on a given surface area of substrate 1.

As shown in Figure 3, after fabrication of the ridge waveguide 7 the whole structure is planarised, i.e. the waveguide 7 is surrounded by a low refractive index layer 8. This may be formed of any dielectric material with a refractive index lower than silicon such as for example CVD deposited silicon oxides or nitrides or spin on glasses. This layer 8 serves several functions. It provides a flat surface onto which an OLED can be

deposited so as to ease manufacture, it provides a well characterised low refractive index material to surround the waveguide 7 in order to improve the waveguide properties and it provides some mechanical protection to the waveguide 7. The planarisation with a low refractive index glass can be achieved in several ways. In one example, Chemical Vapour Deposition (CVD) is used to deposit a silicon dioxide layer 8 around the waveguide. Alternatively, spin on glasses can be deposited. This deposition will give an uneven surface covering the whole device. Following the deposition the glass layer 8 can be planarised back to the top of the silicon waveguide using either a chemical etchant or by chemical mechanical polishing, so as to leave the structure shown in Figure 3.

This waveguide structure 7 is now suitable for the fabrication of a rare earth based OLED 13, as shown in Figure 4. The anode for the OLED 13 can either be the surface of the silicon 3 or an overlayer of Indium Tin Oxide (ITO). If ITO is used, a thin layer 9 of ITO is sputtered over the device and patterned using photolithography so that it covers the active region of the waveguide 7. Following this deposition, organic layers 10, 11 are deposited to form the OLED. In the simplest case this consists of a hole transporting layer 10 such as N,N' diphenyl-N,N'-bis(3-methylphenyl)-1,1'-biphenyl-3,3'-diamine (TPD) and a rare earth based emitting layer 11. The rare earth-based emitting layer may include for example erbium (III) *tris*(8-hydroxyquinoline) (ErQ) but may comprise any rare earth combined with any other suitable organic ligand which allows for transfer of energy into the internal levels of the rare earth ion. This may include the use of organic ligands which are designed so that their excitons are at energies resonant with internal levels in the rare earth ion. However, this may not be an overriding concern as, even for molecules where the exciton energies in the organic ligands are very different from the levels in the rare earth ion, coupling of the energy between them is still possible. The emitting layer 11 may also be the electron transporting layer.

A number of refinements to this simple structure are possible. These include the use of different hole transporting materials, extra layers to improve hole or electron injection from the contacts into the device, exciton blocking layers or the use of dopant materials

within the charge transport layers 10, 11. Following the deposition of the OLED a top cathode contact 12 is formed by the evaporation of a suitable metal electrode.

Figure 5 shows a plan view of the device shown in Figure 4. In order to obtain the largest gain region the OLED 13 covers the whole of the coiled waveguide structure 7. In order to prevent short-circuits between the two contacts 9, 12 the ITO anode 9, hole transport layer 10, emitting layer 11 and metal cathode 12 have slightly different evaporation patterns as shown in Figure 5.

A second embodiment of a device in accordance with the invention will now be described with reference to Figures 6 and 7. As an alternative to placing the OLED 13 on the surface of the waveguide 7 and using the evanescent wave in the OLED 13 to couple and provide gain, the OLED may be integrated directly into the silicon waveguide. In such an embodiment the OLED 13 is deposited on the ridge waveguide 7 in a similar manner to that described above. However, rather than using metal as the top contact 12 the device is covered with a further layer of silicon. This is again etched into the waveguide pattern forming an OLED which is in the heart of the waveguide and thus at the centre of the guided mode.

For this embodiment the fabrication procedure up to Figure 3 remains the same although the thickness of the waveguide layer 7 is lower, the precise thickness depending on the wavelength of light for which the waveguide is designed. The ITO layer 9 and the organic layers 10 and 11 are then deposited as before but instead of the metal top contact 12 (see Figure 4), a doped silicon layer 14 is deposited to act as the top contact as shown in Figure 6. The thickness of this top silicon layer 6 is such that the OLED is incorporated in the centre of the waveguided mode. This depends on the wavelength of light for which the device is designed to operate. Following the deposition of this silicon layer 14 it is patterned and etched using standard photolithographic and etching techniques, as shown in Figure 7, to produce a top contact 15 matching the pattern of the underlying silicon waveguide 7. The surface of the wafer is then be planarised 16 using the same techniques as before.

Although the device has been described as a 'buried-ridge' waveguide formed on a silicon-on-insulator (SOI) substrate, it will be appreciated that other configurations will fall within the scope of the invention. For example, it is also possible to form a waveguide on a conventional silicon substrate by making the waveguide from layers of dielectric materials deposited on to the silicon. This structure could then be patterned in a similar way to that described for the SOI substrate.

**CLAIMS:**

1. An optical amplifier comprising a silicon-based substrate having a gain region for amplifying an optical signal, an organic light-emitting device containing a rare earth being provided for producing excited rare earth ions in the gain region.

2. An optical amplifier as claimed in claim 1, wherein the gain region is formed by a waveguide on the substrate.

3. An optical amplifier as claimed in claim 2, wherein the waveguide follows a coiled path on the substrate.

4. An optical amplifier as claimed in claim 3, wherein the waveguide is a ridge or buried-ridge waveguide.

5. An optical amplifier as claimed in claim 2, 3 or 4, wherein the waveguide is formed from layers of dielectric material deposited on the substrate.

6. An optical amplifier as claimed in any preceding claim, wherein the substrate is formed from silicon.

7. An optical amplifier as claimed in any preceding claim, wherein coupling means are provided for coupling optical fibres to the amplifier.

8. An optical amplifier as claimed in claim 7, wherein the coupling means are V-shaped grooves in the substrate.

9. An optical amplifier as claimed in any preceding claim, wherein the rare earth is erbium.

10. An optical amplifier as claimed in any of claims 1 to 8, wherein the rare earth is neodymium.

11. An optical amplifier as claimed in any of claims 1 to 8, wherein the rare earth is ytterbium.

12. An optical amplifier as herein described with reference to the accompanying drawings.

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| **Application No:** | GB 0107001.0 | **Examiner:** | Claire Williams |
| **Claims searched:** | all | **Date of search:** | 14 December 2001 |

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**Databases searched:**

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK_Cl (Ed.S): H1C (CH, CBAX) H1K (KEAM, KEAL)

Int Cl (Ed.7): H01S (3/063, 3/0915,3/16, 5/30, 5/04) H01L (51/30) H05B (33/14)

Other: ONLINE: WPI, JAPIO, EPODOC, selected publications

**Documents considered to be relevant:**

| Category | Identity of document and relevant passage | | Relevant to claims |
|---|---|---|---|
| A, E | WO 01/78203 A1 | (Queen Mary and Westfield College) whole document | |
| A, E | WO 01/61797 A1 | (Photon -X Inc) in particular, claims 1 and 11 | |
| Y | EP 0729244 A2 | (AT&T IPM Corp) in particular, see column 5 lines 50 to 57 | 1, 6, 9, 10, 11 |
| Y | Applied Physics Letters, Vol 77, No 12, 9 Oct 2000, Curry et al, "Silicon-based organic light-emitting diode operating at a wavelength of 1.5 μm" whole document | | 1, 6, 9, 10, 11 |

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